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Numerical Simulation of Internal Reconnection Event in Spherical Tokamak

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Abstract

Three dimensional magnetohydrodynamic simulations are executed in a full toroidal geometry to clarify the physical mechanisms of the Internal Reconnection Event (IRE), which is observed in the spherical tokamak experiments. The simulation results reproduce several main properties of IRE. Comparison between the numerical results and experimental observation indicates fairly good agreements regarding nonlinear behavior, such as appearance of localized helical distortion, appearance of characteristic conical shape in the pressure profile during thermal quench, and subsequent appearance of the m=2/n=1 type helical distortion of the torus.

Keywords: spherical tokamak, Internal Reconnection Event, plasma relaxation, computer simulation, thermal quench

1. Introduction

Internal Reconnection Event (IRE) is an energy relaxation phenomenon which has been observed in the spherical tokamak experiments such as START [1-3] and CDX-U[4]. The physical mechanisms of the event have not yet been clarified. In this paper, three dimensional magnetohydrodynamic simulations are executed in a full toroidal geometry to investigate the physical mechanisms of the event, and comparison is made between the simulation results and typical experimental observations of the event. It will be shown that fairly good agreements between them are observed with respect to a couple of key phenomenological features.

IRE observed in experiments is characterized by the following properties. 1) The central value of the plasma pressure falls rapidly in a time scale of around 100 or 200 microsecond (thermal quench), and 2) the heat energy is transported from the core to the edge rapidly, but 3) the event is not so destructive as to destroy the whole torus, and a property of resiliency is observed. 4) The net toroidal plasma current increases in 10 percent or more like a spike, following the occurrence of the thermal quench. 5) The event is accompanied by low m and n modes. 6) Vertical elongation and/or helical distortion of the poloidal cross section is observed. IRE is considered to be important partly because in some cases it causes subsequent occurrence of disruption in spite of the basic nature of the resiliency, and partly because each time it occurs about 30 percents of the total heat energy confined in the torus is lost. Thus, the nature of the event need to be well understood before we consider about realization of a fusion reactor by using the spherical tokamak concept.

2. Phenomenology of IRE

Shown in Fig. 1 are typical snapshots of CCD camera image just when IRE occurs in the START spherical tokamak experiment [5] by courtesy of Drs. A. Sykes and M. Gryaznevich. The images are taken to show the overall structure of the torus. Figure 1 (a) shows an image of a high time-resolution monochromatic camera (the time-resolution is about 30 microseconds), which is taken at a moment corresponding to an early stage in the process of IRE. The dark region in the image corresponds to a hot plasma region, and the bright area corresponds to relatively colder plasma. It should be noted that a "mysterious" pattern is observed in the bright area ; the bright area has a helical structure which extends in the periphery from the top down to the bottom of the torus. The most noticeable property is that the helical structure exists only in the local area around the torus. This pattern of the localized helical distortion is often observed in the CCD image of IRE [5].

Shown in Fig. 1 (b) is a CCD camera image which is taken at slightly later stage in the process of IRE compared with Fig. 1 (a) (the time-resolution for this image is about 100 microseconds). What should be noticed in the image is the formation of bright areas with a characteristic conical shape, which are formed both on the top and bottom of the torus.

It has been observed that the thermal quench in IRE proceeds in two steps. A helical distortion of the overall torus structure, which has a nature of a m=2/n=1 mode (m and n are the poloidal and toroidal mode number, respectively), is often observed in the second step, as is shown in Fig. 1 (c) and (d).

3. Simulation Results

We execute magnetohydrodynamic simulations in a toroidal geometry, of which details of the modeling are described in the previous paper [6]. The governing equations consist of the full set of resistive and compressible magnetohydrodynamic equations. The equations are solved in the cylindrical coordinate. All the variables are normalized to the major radius of the simulation region and the toroidal magnetic field on the magnetic axis of the initial equilibria, therefore, the unit of time is the Alfven transit time(τ_A) encircling the magnetic axis.

In this paper, we describe simulation results for a case starting from an initial axisymmetric equilibrium for which the central value of the safety factor, q(0), is slightly less than one. More specifically, the aspect ratio A is 1.35, the elongation κ is 1.6, the central beta $\beta(0)$ is 48%, and q(0) is 0.91. The simulation results reproduce several main properties of IRE.

First, we describe the plasma behavior which corresponds to the first step in the process of IRE. The central value of the plasma pressure falls in a time scale of around 100 τ_A (1 τ_A roughly corresponds to 1 microsecond), and the heat energy is transported from the core to the edge rapidly, but the event is not so destructive [6]. The time evolution of each Fourier component of the magnetic energy, as is shown in Fig. 2, indicates that the noticeable property in the linear growth of modes are the simultaneous excitation of multiple number of low n modes on the q=1 surface. In this case, m=1/n=1 and m=2/n=2 modes are the dominant ones, which grow together with the similar growth rates. The stage up to the time t = 150 τ_A may be called the "linear stage", where each mode grows independent of other modes. In the later stage, after t = 150 τ_A , the mode coupling effects becomes significant, and many higher n modes are seen to be excited. This stage may be called the "nonlinear stage". In this stage, we find a notable property with respect to relative phase among the modes becomes apparent. Namely, a spontaneous phase-alignment mechanism is induced through nonlinear coupling between the dominant two modes, by which both modes develop while keeping a specific aligned phase relation with each other.

Because of this nature, in the real space, the perturbation in the torus does not grow uniformly around the torus, but expansive bulge-like deformation grows especially at a local region in the toroidal direction where the alignment in the positive perturbation occurs, as is shown in Fig.3. In the linear stage, both of the dominant modes have the nature of an internal mode. In the nonlinear stage, however, those aligned modes grow so much that even the surface of the torus is deformed.

In the highly nonlinear stage, the heat energy is rapidly transported from the core to the edge region by convection due to the excited modes, which appears as the collapse in the pressure profile. It is interesting to note that magnetic reconnection between the field lines in the torus and ambient fields are induced on the periphery of the torus at the local toroidal region where the bulge-like perturbation mainly grows. A part of field lines in the torus is directly connected with the external field lines due to the reconnection. The heat energy transported from the core to the edge of the torus is expelled to the external region along the reconnected field lines, which is found to occur rather impulsively. As is shown in Fig.4, the expelled pressure is transmitted helically along the field lines in the external region. Thus, the characteristic conical shape in the pressure profile is formed both on the top and bottom of the torus.

The excessive heat energy initially stored in the torus is expulsed from the torus in this way, and the torus plasma becomes linearly stable because of the expulsion and redistribution of the plasma pressure. Thus, the deformation of the torus caused by the unstable modes is gradually relaxed, and the torus comes back to an axisymmetric configuration, as is shown in Fig. 2. As is stated above, the computation starts from the initial condition for which q(0) is slightly less than one. At this stage after the relaxation process of the first step, however, it is interesting to note that the value of q(0) is modified to be slightly greater than one, more specifically, q(0) becomes about 1.2. Because of the changes in the profile of the safety factor and the pressure profile, as well as the reduction in the peak pressure value, the m=1/n=1 and the m=2/n=2 modes are not unstable anymore at this stage. Instead of those modes, it should be noted that another kind of unstable mode is excited due to the change in the plasma profile, which is identified as m=2/n=1 type mode. An analysis of the energy principle for this mode indicates that the current driven term is greater than the pressure driven term, thus the nature of the mode is different from the unstable modes growing in the first step for which the pressure driven term is dominant. This m=2/n=1 mode causes the occurrence of the second step thermal quench. As is observed in Fig. 2, the saturation level of this mode is higher than the modes in the first step. As is shown in Fig. 5, the helical distortion occurs in the overall structure of the torus as the growth of the mode.

4. Discussion

Nonlinear simulations of Internal Reconnection Event in Spherical Tokamak are executed. The processes of the nonlinear time development agree with the observations in spherical tokamak experiments in several points as follows.

1. Occurrence of the thermal quench and the good agreement in the time scale.
2. Appearance of the localized helical distortion (see Fig. 1 (a) and Fig. 3).
3. Appearance of the characteristic conical shape in the pressure profile (see Fig. 1 (b) and Fig. 4).
4. The thermal quench proceeds in two steps.

5. Appearance of the m=2/n=1 type helical distortion (see Fig. 1 (c)(d) and Fig. 5).

We consider that the process observed in this paper is a mechanism that can expel "unnecessary" heat energy to the ambient region quickly. Owing to the existence of such mechanism, the spherical tokamak can efficiently readjust its own profile without destroying the whole torus while keeping the favorable property of the resiliency. Otherwise, a destructive process can occur, which may be called major disruption.

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Figure Captions

Fig.1 CCD camera images of the START spherical tokamak experiments when IRE is observed by courtesy of Drs. A. Sykes and M. Gryaznevich. (a) Appearance of the localized helical distortion. (b) Appearance of the characteristic conical shape in the pressure profile. (c) Appearance of the m=2/n=1 type helical distortion. (d) Same as (c) but seen from different angle.

Fig.2 Growth of perturbation in the magnetic energy for each toroidal Fourier mode n in the simulation result.

Fig.3 Time development of the three-dimensional profiles of the plasma pressure and magnetic field lines in the simulation result, which shows formation of localized helical distortion.

Fig.4 Time development of the pressure profile, which shows formation of the characteristic conical shape on the top and bottom of the torus.

Fig.5 Growth of the m=2/n=1 type helical distortion in the simulation result. (a) and (b) are viewed from the different angles, perpendicular to each other.

(a)

(b)

(c)

(d)

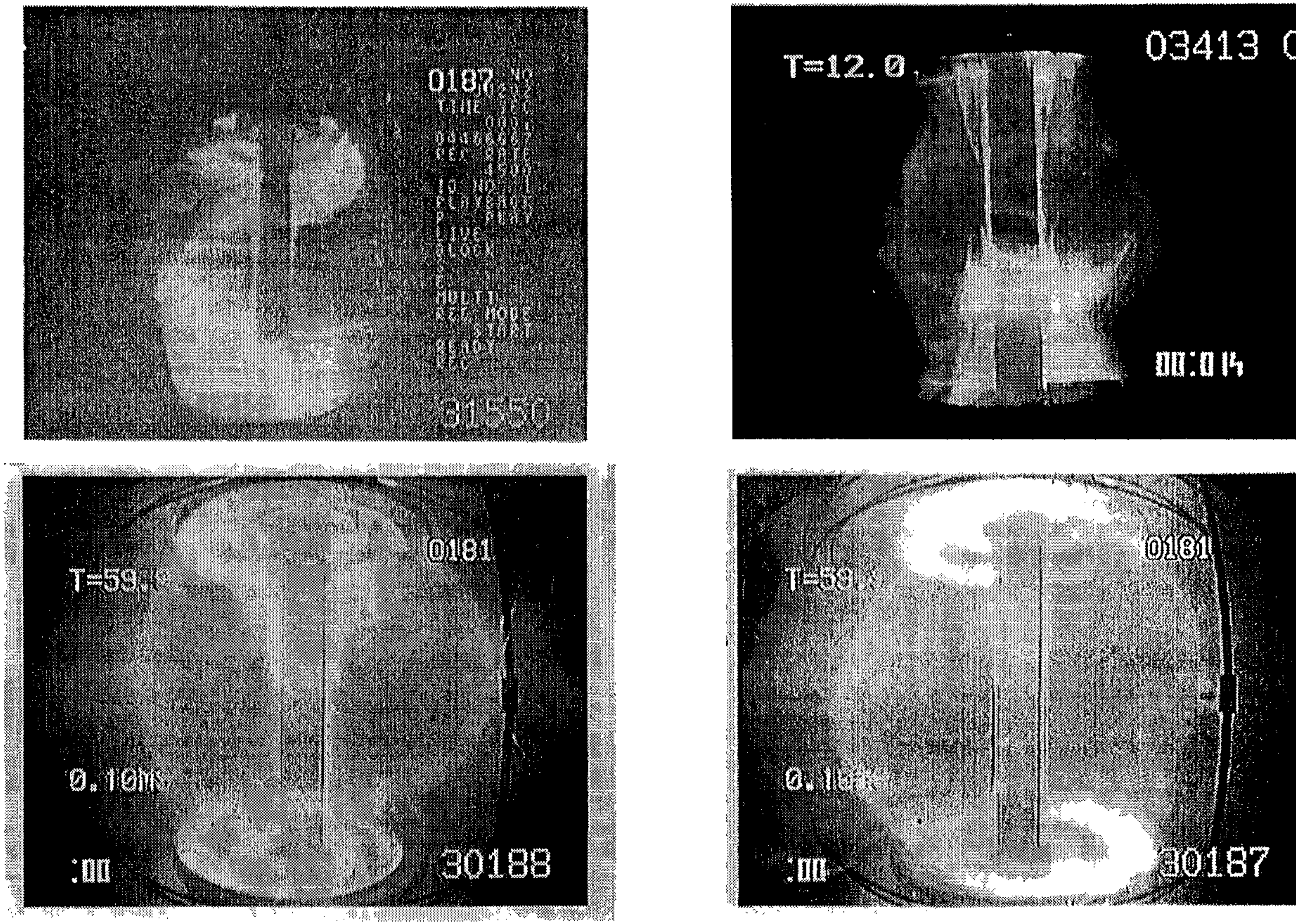


Fig.1

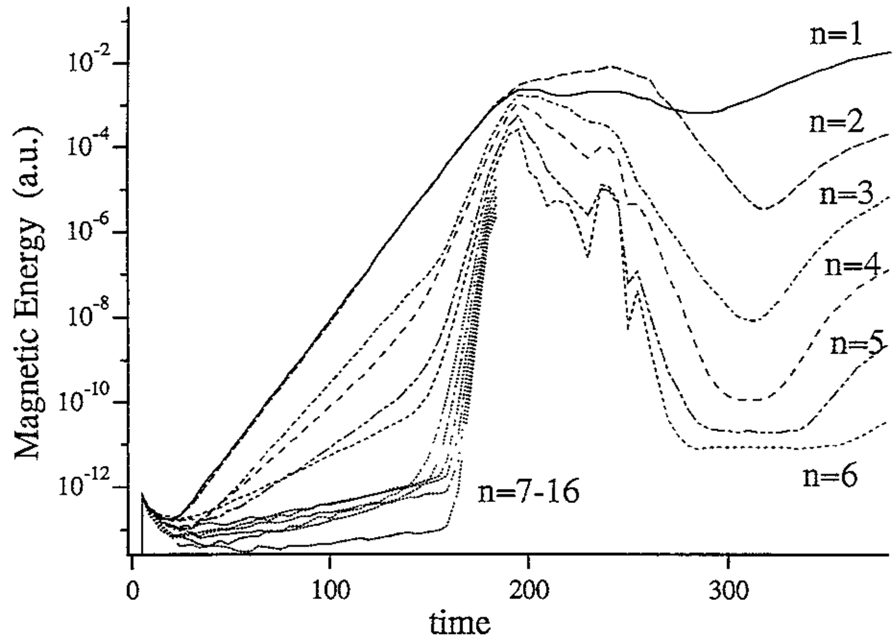
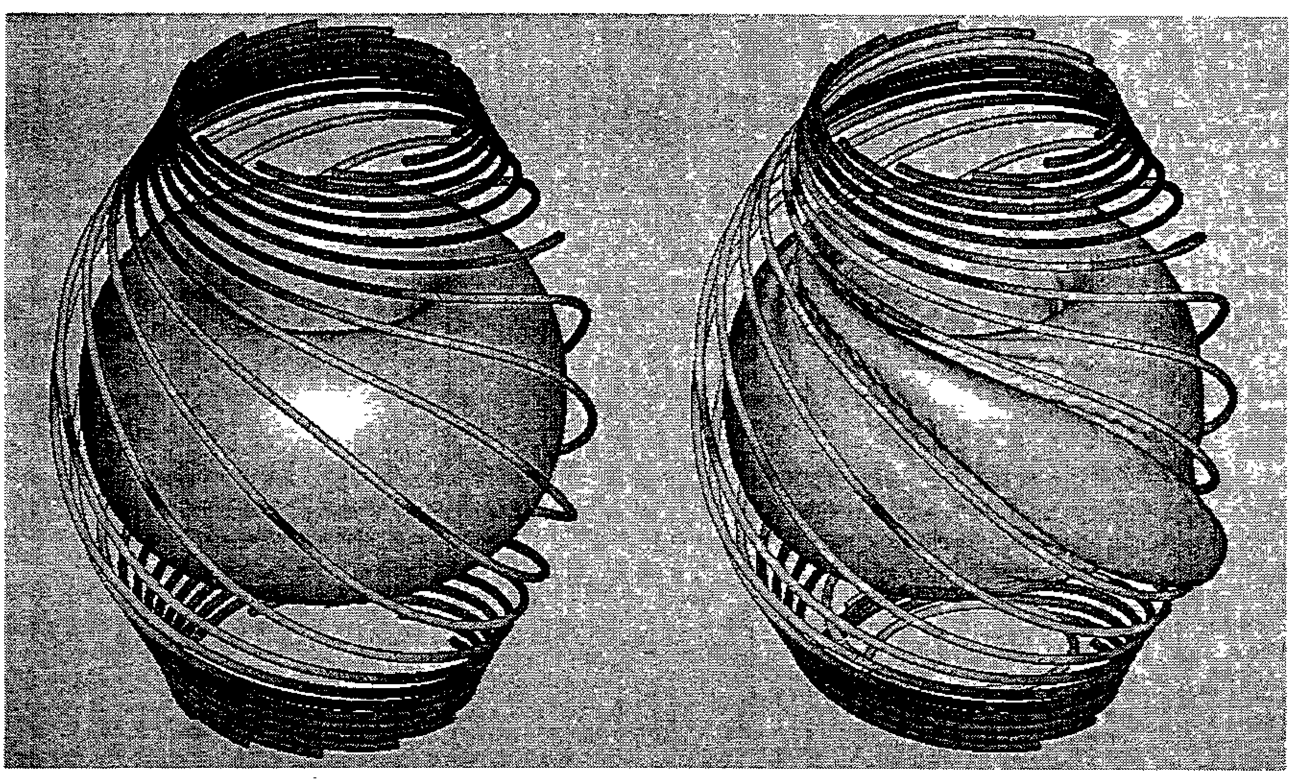


Fig.2



t= 0 τ_A t=197 τ_A

Fig.3

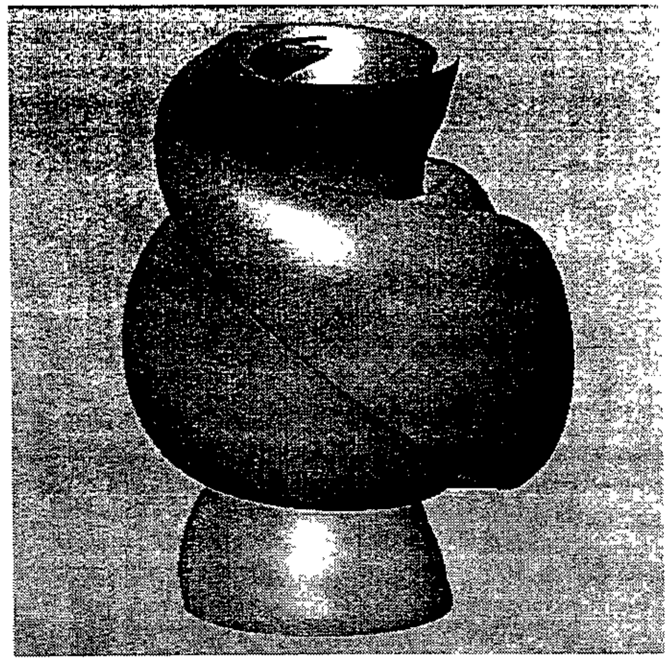
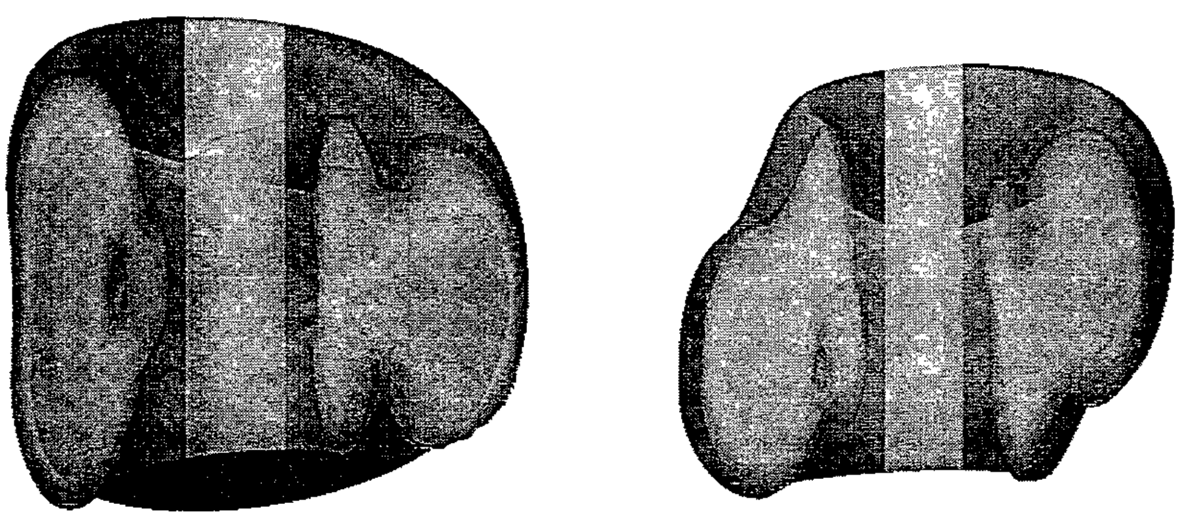


Fig.4



(a) (b)

Fig.5

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